THE PAN-AMERICAN CLIMATE STUDIES SOUNDING NETWORK

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A pilot balloon network funded by NOAA for climate research has proved, over nearly a decade, to be a microcosm of the problems facing the global atmospheric sounding network.

FIG. 1. Venezuelan Air Force observers at San Fernando de Apure tracking a pilot balloon. Usually one observer follows the balloon and reads the angles while another calls out the time and records the data.

The fundamental problem preventing the establishment of a dense radiosonde network in many parts of the world is the high cost of radiosonde observations compared with the available budgets of most meteorological services. Many developing coutries, concentrated in the tropics, rely on international donations of radiosondes for continued operation, which often results in long gaps in the observing record, a poor sampling density, and an inhomogeneous climate record from the use of different radiosondes (Gaffen 1994) without sufficient overlap and comparison testing as called for by the Global Climate Observing System (GCOS) monitoring principles (WMO 2001).

Although limited budgets are most often cited as the reason for the lack of radiosonde observations in developing countries, in part this simply reflects the perceived lack of ▶

value of the observations relative to their cost. Today, in many countries in Latin America, Africa, and Asia, the monthly salary of an observer in a national meteorological service may be comparable to the cost involved in making only *one* or two global positioning system (GPS) radiosonde observations. The value of a particular radiosonde observation is usually difficult to demonstrate for local weather forecasting applications in developing countries in the tropics, where changes in the weather may be relatively subtle and of a small spatial scale, where forecasts are usually neither quantified nor systematically verified, and where increasing reliance on forecast and analysis products disseminated via the World Area Forecast System (WAFS) or via the Internet may give the impression that local observations are not as critical as they once were. After all, forecast products are disseminated daily via the Internet or WAFS whether or not a particular country's radiosonde observations are made on any particular day, and few forecasters can detect any difference in accuracy of the products that are received. Why, then, should there be any pressure to fund such expensive observations, given that they do not apparently make much difference?

For both research and forecasting activities the upper-air sounding network is not very dense over most parts of Central and South America, and even where the networks are thought to be acceptable, many smaller-scale features can remain unresolved. This is the situation in Central America, which, while appearing to have an acceptable station density compared with some other regions, has no measurements of the strong and variable gap flows across the Isthmus of Tehuantepec or across Nicaragua. These gap flows strongly impact the oceanic circulation and sea surface temperature patterns downstream over the eastern Pacific Ocean (Chelton et al. 2000; Xu et al. 2005).

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THE PACS-SONET. Several factors in the mid-1990s encouraged the development of a research-based upper-air observing system for Latin America. The Inter-American Institute for Global Change Research (IAI) initiative fostered discussion of the needs for monitoring climate variability and climate change in the Americas. One such IAI-supported meeting in Panama in 1994 discussed the notion of "sustainable" observing networks for climate monitoring activities. The IAI recommendations stated that, to ensure long-term sustainability for the purpose of documenting climate variability for research activities, observing systems needed to be "robust, inexpensive, and real-time where necessary" (IAI 1995). A second activity, the evolution of the National Oceanic and Atmospheric Administration (NOAA)-supported Equatorial Pacific Ocean Climate Studies (EPOCS) program into the Pan-American Climate Studies (PACS) program provided a potential funding means to encourage measurement campaigns in Latin America.

To improve upper-air climate monitoring across data-poor parts of Latin America one might have suggested simply increasing the number of radiosonde observations. However, given that once-daily upper-air soundings at a single site employing GPS wind-finding radiosondes may cost ~\$75,000 yr^{-1} for the radiosondes alone, other alternatives had to be considered for a research program such as PACS that had a budget of ~\$2 million yr^{-1} for funding all of its research activities. The National Severe Storms Laboratory (NSSL) experience with two projects over northwestern Mexico in the early 1990s suggested a possible strategy. Both the 1990 Southwest Area Monsoon Project (SWAMP-90; Reyes et al. 1994) and the 1993 Experimento Meteorologico de Verano (EMVER-93) showed that it was feasible to establish temporary networks of pilot balloon stations to provide relatively inexpensive wind information into the lower–middle troposphere, and under favorable conditions (few clouds, light winds, and daylight) into the upper troposphere.

Although pilot balloon observations (Fig. 1) provide only wind information, and have well-known limitations resulting from cloudiness, the synoptic variability of winds at low latitudes generally shows a larger signal-to-noise ratio than either temperature or humidity variations, and wind data generally have a larger impact in initializing numerical weather prediction models, especially in the tropics (Bengtsson and Hodges 2005; Zagar et al. 2004; Ramamurthy and Carr 1988). This is fortunate from an economic perspective, because a pilot balloon observation is actually considerably less expensive to make than a radiosonde observation. The SWAMP-90 and EMVER-93 experiences showed that it was possible to operate a network of ~10 pilot balloon sites for the cost of a single radiosonde station, because the direct cost of a 30-gm pilot balloon observation may be only 5%–10% the cost of a GPS–radiosonde observation.[1]

An additional value of pilot balloon observations for climate research studies is not commonly recognized. The technology to make pilot balloons has not fundamentally changed since their inception almost 100 yr ago, and their historical record in many locations is several decades longer than that for radiosonde observations (see Fig. 1 in Ewen et al. 2008). For example, in 1919 the United States operated approximately 20 pilot balloon stations, while radio-tracked wind-finding radiosonde stations did not become numerous until the late 1940s. Thus, detecting trends with pilot balloon wind data (and quantities derived therefrom) should be considerably less complicated than using radiosonde data for trend detection, where sensor technology for measuring temperature and humidity have changed over the past 50 yr, and vary among the many radiosonde manufacturers (WMO 2006). Even wind-finding procedures have changed; while all techniques have involved tracking the radiosonde [whether using radiotheodolites, radionavigation signals (e.g., Loran or Omega), or most recently with GPS satellite signals], the resultant winds have differing characteristics, depending on the time-averaging procedures.

Initial establishment of a sounding network. The opportunity arose in 1996 to apply some of the lessons that had been learned during the Mexican field programs of the early 1990s. A proposal was formulated for, and eventually approved by, NOAA's PACS program that involved the establishment of a network of 12 pilot balloon stations (and one radiosonde station on Cocos Island in the eastern Pacific), ranging from southern Mexico to northern Peru (Douglas and Fernandez 1997; Fig. 2). The original objectives of the proposed work were varied, and included identifying the circulation anomalies associated with wet and dry days over Central America during the summer of 1997, describing the amplitude (via twice-daily observations) of the diurnal variation of the wind field at these sites, and determining whether large differences existed between the widely used National Centers for Environmental Prediction (NCEP) reanalyses and in situ sounding observations in data-sparse areas of the eastern tropical Pacific and the surrounding coastal regions. The two island sites and the coastal plain sites in Ecuador and northern Peru were established to help describe the cross-equatorial flow, with the aim being to relate these fluctuations to the rainfall variations over Central America.

The network that was developed to make the proposed measurements came to be known as the PACS-Sounding Network (SONET). The PACS-SONET was similar to earlier Mexican field programs (Douglas 1995; Douglas and Li 1996) in employing low-cost observing systems. However, PACS-SONET differed from those programs in its multinational scope (involving sites in seven countries) and its relatively long duration for a field program (6 months).

EVOLUTION OF THE PACS-SONET. The original NOAA funding supported the establishment of 12 sounding sites for an expected 6 months. However, the onset of the strong El Niño of 1997/98 led to an extension and expansion of the PACS-SONET, and further climate research objectives in South and North America motivated requests for two 3-yr extensions to the original PACS-SONET. Although funding for the PACS-SONET activities ended in April 2006, six Colombian stations continued observations through November 2006, and several other sites ended observations in early to mid-2007, using the remaining stocks of balloons and gas. The history of the actual observations (Fig. 3) is irregular because of funding variations, delays in balloon shipments, problems with gas supplies in the different countries, and a host of other problems often unique to a particular country. Table 1 describes the stations that made observations, and indicates their primary scientific justification. The table also shows that there was considerable diversity among the institutions that participated in PACS-SONET, though many were national meteorological services.

Adapting to the 1997/98 El Niño. The original PACS-SONET was approved very late in 1996 and the initial setup of stations began in April 1997. The intent was to operate the network for the boreal warm season of 1997 to describe rainfall variability over Central America. However, during the initial setup of the Ecuadorian and Peruvian stations in late April and

[1] This fact is evident to many Asian and African countries, where pilot balloon observations are made routinely.

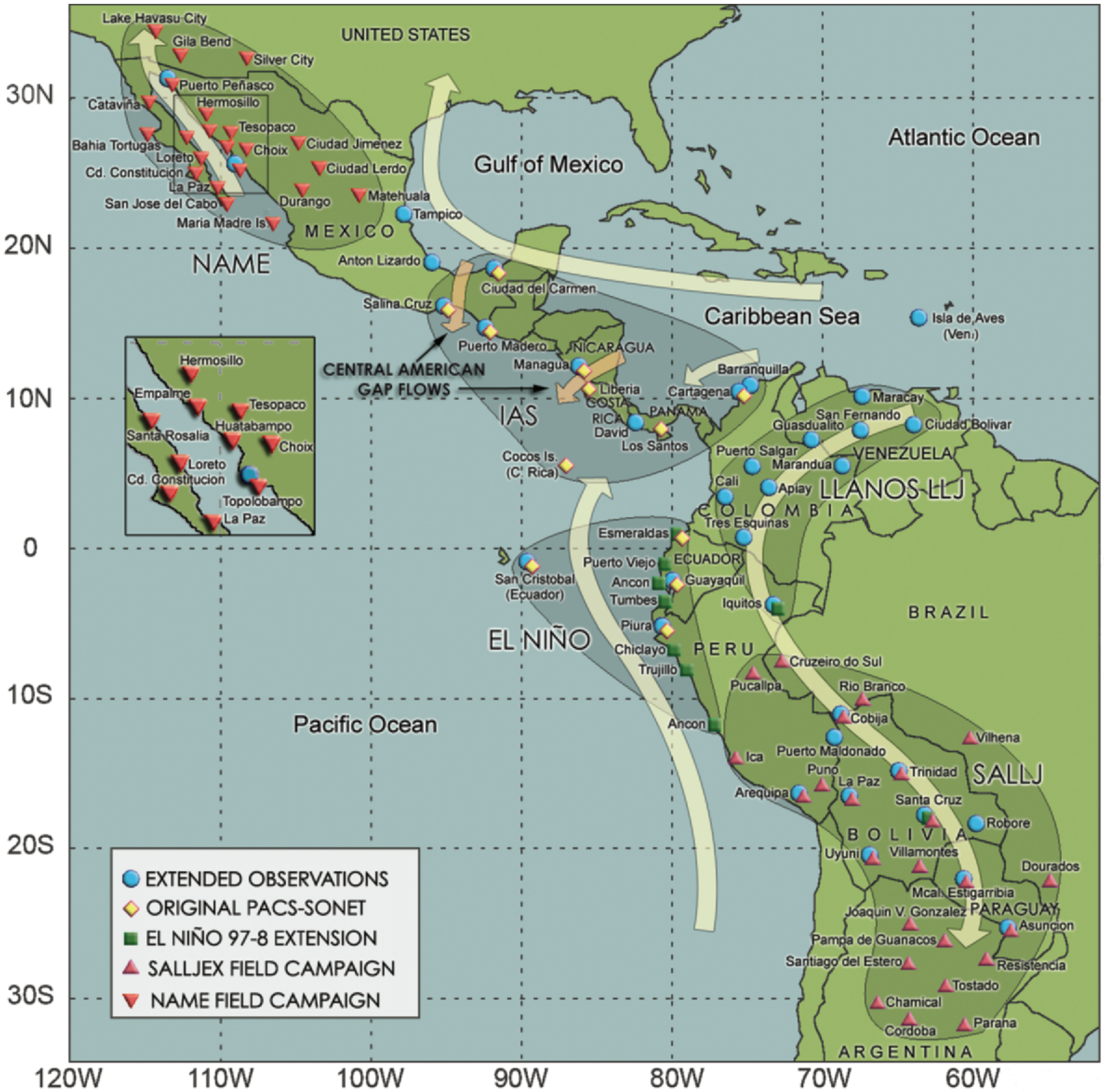

FIG. 2. Map showing the locations where pilot balloon observations have been made since 1997 as part of PACS-SONET. Geographical focus of the network is also shown by shading and schematic low-level streamlines; these include the SALLJ, the coastal El Niño domain, the Llanos Low-Level Jet (LLJ) region, the Inter-American Seas (IAS) region, and the region of the NAME. The different colors and symbols show where temporary sites were established during the SALLJEX, NAME, and the El Niño 1997/98 field programs.

early May 1997, it was apparent that the early phase of an El Niño warm event in the eastern Pacific was underway. By the end of the 6-month measurement program of PACS-SONET it was clear that conditions had not been representative of "normal" warm-season conditions over Central America. This led to a request, which was approved, to extend the operation of the original PACS-SONET stations and to establish additional stations in Peru and Ecuador to better monitor the anomalous conditions that were expected in early 1998. Seven new pilot balloon sites were established (see Fig. 2), along with special rain gauges, prior to the onset of heavy rains over the region in early 1998. Although extensive low cloudiness limited the height coverage obtained by many of these soundings, and there were logistical complications because of flooding, these data have been useful in relating synoptic variations in the coastal rainfall over northern Peru and coastal Ecuador to fluctuations in the intensity of the synoptic flow over the region (Douglas et al. 2008).

The El Niño modification to PACS-SONET highlighted the value of using simple wind sounding systems. The short notice available for planning the

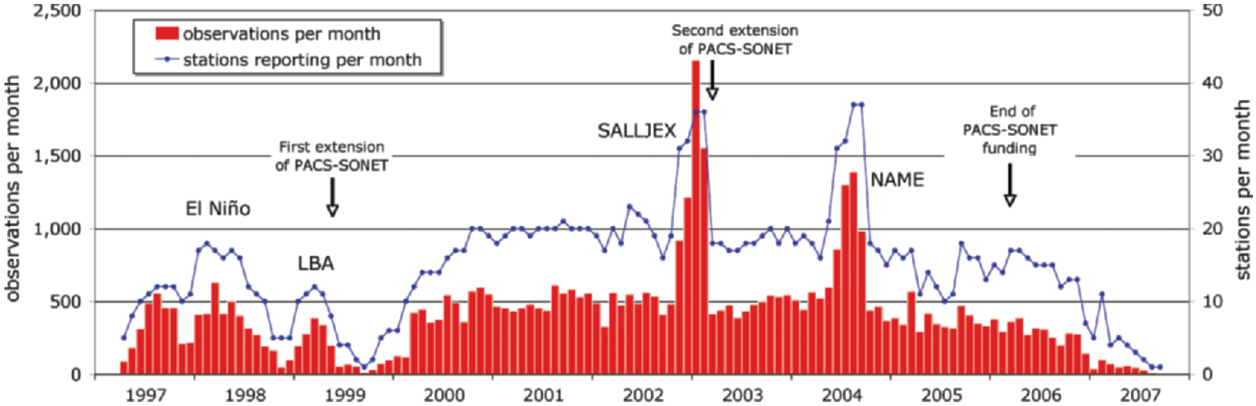

Fig. 3. Observations and number of stations reporting each month during the PACS-SONET. Key events affecting the frequency of soundings are indicated; see text for details. Note that observations continued well after the official end of the project.

special observations (less than 3 months) would normally preclude the formal planning of field research activities by most funding organizations because the deployment pools for research equipment, such as ships, aircraft, portable radars, or even radiosonde systems, are usually committed with much longer lead times. PACS-SONET was able to obtain old, but functional, theodolites from National Weather Service (NWS) facilities in Kansas City, Missouri, on short notice and ship these to the necessary countries. Then, only training of new observers and arranging for balloon inflation gas was needed to start observations.

Extensions into the region of the east Andean low-level jet. One small aspect of the 1998 PACS-SONET El Niño special observations was crucial in extending the PACS-SONET widely into South America. Pilot balloon observations at Santa Cruz, Bolivia, not an originally proposed PACS-SONET site, were motivated by interest of the Variability of the American Monsoon Systems (VAMOS) community in the low-level jet (LLJ) that was appearing on global and regional analyses over that part of South America. The LLJ was not sampled by any upper-air stations of the region, and it appeared worthwhile to establish a pilot balloon site at Santa Cruz as part of the El Niño observational expansion. Although the Santa Cruz observations were made for less than 3 months and were limited by frequent low cloudiness, they revealed a strong and variable low-level jet (Douglas et al. 1998). These observations complemented much earlier studies based mostly on Argentinean observations (Berri and Inzunza 1993), indicating the importance of the low-level jet in moisture transport east of the Andes.

The logistical success of PACS-SONET in arranging the Bolivian observations on short notice led to an offer to participate in the 1999 Tropical Rainfall Measuring Mission (TRMM) Large Scale Atmosphere–Biosphere Experiment in Amazonia (LBA) validation field program concentrated in the Brazilian state of Rhondonia, bordering northeastern Bolivia. For this program a network of five pilot balloon sites were established in Bolivia, including both lowland and altiplano (~4 km above sea level) sites. This second year of observations at Santa Cruz showed a considerably weaker LLJ, which, taken with the 1998 observations, indicated that the east Andean LLJ had strong interannual as well as synoptic variability. This strengthened the notion that long-term observations would be worthwhile for monitoring the atmospheric circulation variability in this region, and additional measurements were continued in Bolivia for many months, despite logistical complications and a difficult gas supply situation. The Bolivian pilot balloon observations from 1998 to 2002, together with observations from two Paraguayan sites, helped to stimulate studies of the low-level jet (Marengo et al. 2002, 2004). The value of these observations (relative to their cost) led to the temporary establishment of 20 pilot balloon sites in five countries (Table 2) during South American Low-Level Jet Experiment (SALLJEX), carried out in late 2002 and early 2003 (Vera et al. 2006), during which approximately 4,000 observations were made over a 3-month period.

Monitoring the North American monsoon. As part of the first 3-yr extension of the PACS-SONET in 2000, three additional stations were established in Mexico. Arrangements for the original Mexican pilot

Table 1. Characteristics of PACS-SONET pilot balloon stations, including their main scientific objectives.

Original PACS-SONET	Country	Institution	Latitude	Longitude	Elevation (m)	Period Operating	Count of obs	Objective
Cartagena	Colombia	CIOH	10.15°N	75.22°W	12	06/97–01/05	936	Description of topography-anchored low and Intertropical Convergence Zone (ITCZ)
Cocos Island	Costa Rica	IMN	5.54°N	87.05°W	2	05/97–11/97	180	Variability of flow associated with wet/dry periods in Central America (CA)
Liberia	Costa Rica	IMN	10.60°N	85.54°W	70	04/97–04/98	370	Variability of flow associated with wet/dry periods in CA
Esmeraldas	Ecuador	INAMHI	0.97°N	79.63°W	80	08/97–09/98	310	Seasonal evolution of wind field associated with El Niño–Southern Oscillation (ENSO)
Galapagos	Ecuador	INAMHI	1.20°S	89.32°W	5	06/97–09/04	1,284	Variability of cross-equatorial flow associated with ENSO
Guayaquil	Ecuador	ESPOL	2.44°S	79.66°W	100	07/97–05/02	932	Variability of flow associated with wet/dry periods in CA
Frontera	Mexico	SMAM	18.52°N	92.65°W	4	04/97–05/99	928	Trade-wind flow across southern Yucatan
Puerto Madero	Mexico	SMAM	14.40°N	92.10°W	3	04/97–05/05	1,653	Tropical wave monitoring in the Gulf of Tehuantepec
Salina Cruz	Mexico	SMAM	15.87°N	94.89°W	8	04/97–05/05	3,430	Flow across gap at Isthmus of Tehuantepec
Managua	Nicaragua	INETER	11.83°N	85.87°W	56	04/97–08/07	2,519	Variability of trade winds across Central America
Los Santos	Panama	ETESA	7.94°N	80.74°W	18	05/97–10/97	238	Variability of flow associated with wet/dry periods in CA
Piura	Peru	UDEP	5.50°S	80.33°W	41	05/97–04/07	3,255	Variations of near-coast flow associated with ENSO
El Niño 1997/98	**Country**	**Institution**	**Latitude**	**Longitude**	**Elevation (m)**	**Period Operating**	**Count of obs**	**Objective**
Ancon	Ecuador	INAMHI	2.33°S	80.88°W	34	12/97–07/98	187	Seasonal evolution of wind field associated with El Niño
Portoviejo	Ecuador	INAMHI	1.04°S	80.47°W	44	11/97–02/98	57	Seasonal evolution of wind field associated with El Niño
Ancon	Peru	SENAMHI	11.77°S	77.17°W	30	01/98–06/98	154	Seasonal evolution of wind field associated with El Niño
Chiclayo	Peru	SENAMHI	6.77°S	79.85°W	29	03/98–06/98	147	Seasonal evolution of wind field associated with El Niño
Iquitos	Peru	SENAMHI	4.05°S	72.95°W	104	02/98–09/98	304	Equatorward extent of cold surges during SH cold season
Trujillo	Peru	SENAMHI	8.11°S	79.00°W	34	12/97–06/98	211	Seasonal evolution of wind field associated with El Niño
Tumbes	Peru	SENAMHI	3.57°S	80.46°W	7	01/98–06/98	153	Seasonal evolution of wind field associated with El Niño
Extended observations	**Country**	**Institution**	**Latitude**	**Longitude**	**Elevation (m)**	**Period Operating**	**Count of obs**	**Objective**
Cobija	Bolivia	AASANA	11.04°S	68.78°W	271	07/00–02/04	609	Measure wind conditions upstream from the region of low-level jet (LLJ)
La Paz	Bolivia	AASANA	16.51°S	68.20°W	4,024	02/99–03/04	1,013	Flow over the Bolivian and Peruvian altiplano
Robore	Bolivia	AASANA	18.33°S	59.76°W	277	01/99–03/04	581	Horizontal extent of LLJ flow
Santa Cruz	Bolivia	AASANA	17.76°S	63.15°W	373	01/98–03/04	664	Monitoring flow near region of strongest LLJ east of Andes
Trinidad	Bolivia	AASANA	14.82°S	64.92°W	156	01/99–03/04	896	Wind profiles near the core of LLJ over eastern Bolivia

Uyuni	Bolivia	AASANA	20.46°S	66.86°W	3,669	03/99–12/03	790	Flow over the Bolivian and Peruvian altiplano
Apiay	Colombia	FAC	4.08°N	73.56°W	370	09/05–02/07	373	Description of low-level flow over eastern Colombia
Barranquilla	Colombia	FAC	10.88°N	74.77°W	30	09/05–02/07	203	Variations of Caribbean low-level jet
Cali	Colombia	FAC	3.45°N	76.48°W	965	09/05–02/07	437	Synoptic variability over southwest Colombia
Marandua	Colombia	FAC	5.52°N	68.68°W	87	09/05–02/07	257	Description of low-level flow over eastern Colombia
Puerto Salgar	Colombia	FAC	5.48°N	74.66°W	173	09/05–02/07	340	Description of Inter-Andean Canyon flow
Tres Esquinas	Colombia	FAC	0.75°N	75.23°W	178	09/05–02/07	265	Description of low-level flow over eastern Colombia
Anton Lizardo	Mexico	CAM	19.06°N	95.98°W	3	04/02–06/07	1,771	Validation of radiosonde-derived winds at Veracruz
Cd. del Carmen	Mexico	SMAM	18.64°N	91.84°W	2	03/00–05/06	3,437	Trade-wind flow across southern part of Yucatan
Puerto Peñasco	Mexico	SMAM	31.31°N	113.55°W	3	06/99–10/05	2,004	Variability of the Gulf of California low-level jet
Tampico	Mexico	SMAM	22.28°N	97.85°W	15	03/00–09/06	3,429	Variability of recurving trades along east coast of Mexico
Topolobampo	Mexico	SMAM	25.62°N	109.05°W	12	03/00–12/06	3,572	Insensity and latitudinal extent of Gulf of California surges
David	Panama	ETESA	8.10°N	82.13°W	27	11/97–12/01	838	Variability of flow associated with wet/dry periods in CA
Asuncion	Paraguay	DINAC	25.27°S	57.63°W	83	11/99–09/05	1,493	Measurements near exit region of the east Andean LLJ
Estigarribia	Paraguay	DINAC	22.02°S	60.60°W	155	11/99–09/05	1,055	Monitoring very close to mean position of LLJ over Chaco
Arequipa	Peru	SENAMHI	16.32°S	71.55°W	2,370	11/02–11/06	1,147	Monitoring flow over northern altiplano and Bolivian high
Pto. Maldonado	Peru	SENAMHI	12.58°S	69.20°W	256	02/06–05/07	124	Additional obs at ENSO-monitoring radiosonde site
Cd. Bolivar	Venezuela	FAV	8.25°N	63.92°W	77	03/02–03/05	475	Description of low-level flow over Venezuelan llanos
Guasdualito	Venezuela	FAV	7.25°N	70.73°W	130	10/05–04/06	46	Description of low-level flow over Venezuelan llanos
Isla de Aves	Venezuela	FAV	15.38°N	63.58°W	4	10/05–07/06	42	Island location to monitor trade winds over the Caribbean
Maracay	Venezuela	FAV	10.15°N	67.35°W	440	03/04–08/06	644	Influence of topography on trade wind flow
San Fernando	Venezuela	FAV	7.89°N	67.46°W	47	03/01–08/06	1,492	Description of low-level flow over Venezuelan llanos

Institution acronyms:

AASANA = Administration of Airports and Aerial Navigation Services	CAM = Astronomical and Meteorological Center/Naval School
CIOH = Oceanographic and Hydrographic Research Center	DINAC = National Direction of Civil Aeronautics
ESPOL = Higher Polytechnic School of the Coast	ETESA = Electric Transmission Company
FAC = Colombian Air Force	FAV = Venezuelan Air Force
IMN = National Meteorological Institute	INAMHI = National Meteorological and Hydrological Institute
INETER = Nicaraguan Institute for Territorial Studies	SMAM = Mexican Navy
SENAMHI = National Meteorological and Hydrological Service	UDEP = University of Piura

balloon sites had been made with the Mexican Navy, a consequence of contacts made during a previous NSSL-supported educational activity in Mexico. The Mexican Navy had offered to provide observers and gas supplies for twice-daily observations, provided that PACS-SONET trained the observers and helped with other site requirements. Two of the new sites were established in northwestern Mexico to help monitor the low-level flow along the Gulf of California, an object of the previous NSSL field campaigns in Mexico. Observations from these sites, ranging from 5 to 7 yr, should be useful for describing the interannual variability of the summertime low-level jet over the Gulf of California, especially near the northern end of the gulf, where the southerly jet is strongest and where routine atmospheric soundings had never been made. The PACS-SONET observations can help place into context observations from the North American Monsoon Experiment (NAME), carried out during the summer of 2004 over the region (Higgins et al. 2006). One of the main objectives of NAME research is determining the relationship between enhanced southerly wind events over the Gulf of California (so-called "surges") and rainfall over the surrounding region. During NAME, as during the previous SALLJEX, a special network of 20 sites (Table 2) was established for approximately 3 months to provide a denser coverage of wind soundings than was possible from the radiosonde network alone. Both the SALLJEX and NAME pilot balloon networks, though funded separately from PACS-SONET, used the same observing procedures, data transmission, and quality control steps.

CHALLENGES IN DEVELOPING THE PACS-SONET.

Finding partners. One of the initial difficulties in establishing a sounding network was the identification of suitable institutional partners with which to work. In many countries there is more than one meteorological service, and aviation or military institutions, which generally already possess an observation and communications infrastructure, can sometimes be more suitable than the institution that is designated as the permanent representative to the World Meteorological Organization. The initial establishment of stations in a particular country often depended more on who replied first to our initial requests for collaboration than to how well suited the institution was to maintain such an activity. Long-term sustainability of stations was originally a secondary issue, because the initial PACS-SONET activity was designed for only 6 months of operation. The collaborating institutions have changed over the years (Table 1), with new participants joining the activity while some others "retired"; for example, the Meteorological Service of Panama was privatized and eliminated the activity.

Selecting observation sites. PACS-SONET sought to establish stations in scientifically valuable locations (see Table 1), but at the same time the sites had to be sustainable and inexpensive to operate. Some sites, such as Salina Cruz, Mexico, and Managua, Nicaragua, were located in topographic gaps in Central America, and there were institutions capable of operating the sites with relatively small investment. Other scientifically valuable locations, such as Cocos Island in the eastern Pacific, could not be maintained because of a lack of personnel, high transport costs to the island, and difficulty in communicating the data. Additionally, not least of all, it was not always clear which institutions would be willing to participate. Capable and willing partners were sought, sometimes at the expense of scientific value of the site. In short, the PACS-SONET suffered from many of the complications involved in establishing any international observing network.

Equipment and supplies. The theodolites for PACS-SONET were obtained on long-term loan from a National Weather Service facility in Kansas City; this greatly reduced the initial cost of the PACS-SONET project, because new theodolites can cost ~$8,000 each. Maintenance of the theodolites was an ongoing activity, which necessitated training of personnel in various countries to make repairs and adjustments to the theodolites as needed. A detailed Web site (www.nssl.noaa.gov/projects/pacs/web/MANUAL/index.shtml; in Spanish) was developed to explain most of the basic adjustments and observational procedures to help maintain the equipment and to train new observers.

The 30-gm pilot balloons chosen for PACS-SONET, when inflated to ascend at ~3.8 m s^{-1} with hydrogen gas (slightly different for helium), generally would reach at least 12-km altitude before bursting. Observations of elevation and azimuth angle were made every 30 s until 8 min after launch, and then every minute thereafter. This ensured good vertical resolution, with 1-min averaged winds every 110 m in the lowest ~1.7 km, and 2-min-averaged winds thereafter. Soundings were terminated after 52 min (if followed that long) to reduce observer workload at cloud-free sites. The 30-gm balloon size reduced the purchase and shipping costs and also reduced the quantity of inflation gas needed. There were wide variations in the price (and even availability) of gas among countries in Latin America, varying by almost a factor of 4 between Mexico and

Peru (inexpensive) and Bolivia (most expensive). The number of observations per day was likewise dictated by available funds, with once daily (near 1200 UTC[2]) being the default. In Mexico, and occasionally elsewhere, observations were made twice daily (in early morning and late afternoon) because of lower gas cost, the availability of observers at no additional charge, or the importance of estimating the amplitude of the diurnal cycle of the winds.

Despite the emphasis on inexpensive observing systems, it was recognized that for PACS-SONET to succeed in making the transition from a research project supported for research objectives to a sounding network with both research and operational climate monitoring functions, it would be necessary for each of the participating countries to support portions of the project. Such an effort was successful in some countries (especially Peru, Mexico, and Colombia), but less so in others.

Showing value of the observations through real-time data transmission and display. The PACS-SONET was funded as a research project, and the observations were intended to support research, not as an aid in routine forecasting. As such, little effort was made initially to attempt real-time data transmission. However, it was soon recognized that it would be easier to sustain such observations if they were useful to the institutions helping to make them. Because most institutions benefited primarily through real-time use of meteorological observations it became necessary to convert the PACS-SONET activity from a delayed-reception, research-only mode of operation to a near-real-time flow of data. This required a major effort to improve communications infrastructure and to establish protocols. This ranged from the purchase of fax machines or Internet-provider services, to supplying personal computers for processing observations at the observing sites and training observers in the use of these computers for data editing. The graphical display of the observations in real time was considered particularly important. At most forecast offices in the region the sources of upper-air observations had been principally either WAFS or Internet-based plots, or hand-plotted charts from coded sounding data transmitted over the Global Telecommunications System (GTS). Routine GTS data transmission of the PACS-SONET observations was often not straightforward, and a work-around was devised, whereby these data were transmitted via FTP to a computer at NSSL. The observations were then sent to NCEP for use in their delayed "final" analysis. On good days, up to 10 observations reached NCEP in time for use in the final analysis, but on most days the data reception was less. Plots at different levels were also generated using these data and were displayed on the project's Web site shortly after the data's arrival. These plots, including both the PACS-SONET pilot balloon and routine radiosonde observations, were helpful in error detection and also made the observations available to anyone with Internet access.

EDUCATIONAL ACTIVITIES OF PACS-SONET. The real-time transmission of PACS-SONET data, albeit only partially successful, exposed the more serious problem of actually using the observations for routine forecasting. Many meteorological services in Latin America lack research staff to develop improved forecasting techniques. This situation, coupled with an emphasis on previously established procedures and little time by forecasters to explore alternatives, limited widespread use of the PACS-SONET observations.

Recognizing that the inability to use the PACS-SONET observations was a roadblock to long-term sustainability of the network stimulated a number of educational activities (see Fig. 4). Probably the most successful of these were two full-time courses of 3-week duration—in Bolivia in December 2000 (with ~60 participants, including 11 institutions from five countries) and in Panama in July–August 2001. The Panama course involved 30 Panamanian participants and 50 participants from 21 institutions in nine other countries; the latter were supported by PACS-SONET and U.S. National Weather Service International Activities Office funds. In addition to lectures on basic aspects of tropical and mesoscale meteorology, many topics were unconventional, such as common problems of meteorological services, the cost effectiveness of different observing systems, difficulties in obtaining unbiased information on what meteorological services really need, and what kinds of training and education were needed for meteorological service staff. All courses were carried out in Spanish, because much of the operational meteorological community in Latin America is not fluent in English.

[2] Morning observations were most commonly made about 30 min after sunrise to minimize both the presence of boundary layer cumulus and uncertainties in the ascent rate resulting from boundary layer thermals; this time varied with longitude, but was usually within 1 h of 1200 UTC. Afternoon observations were usually near 0000 UTC, or an hour before sunset.

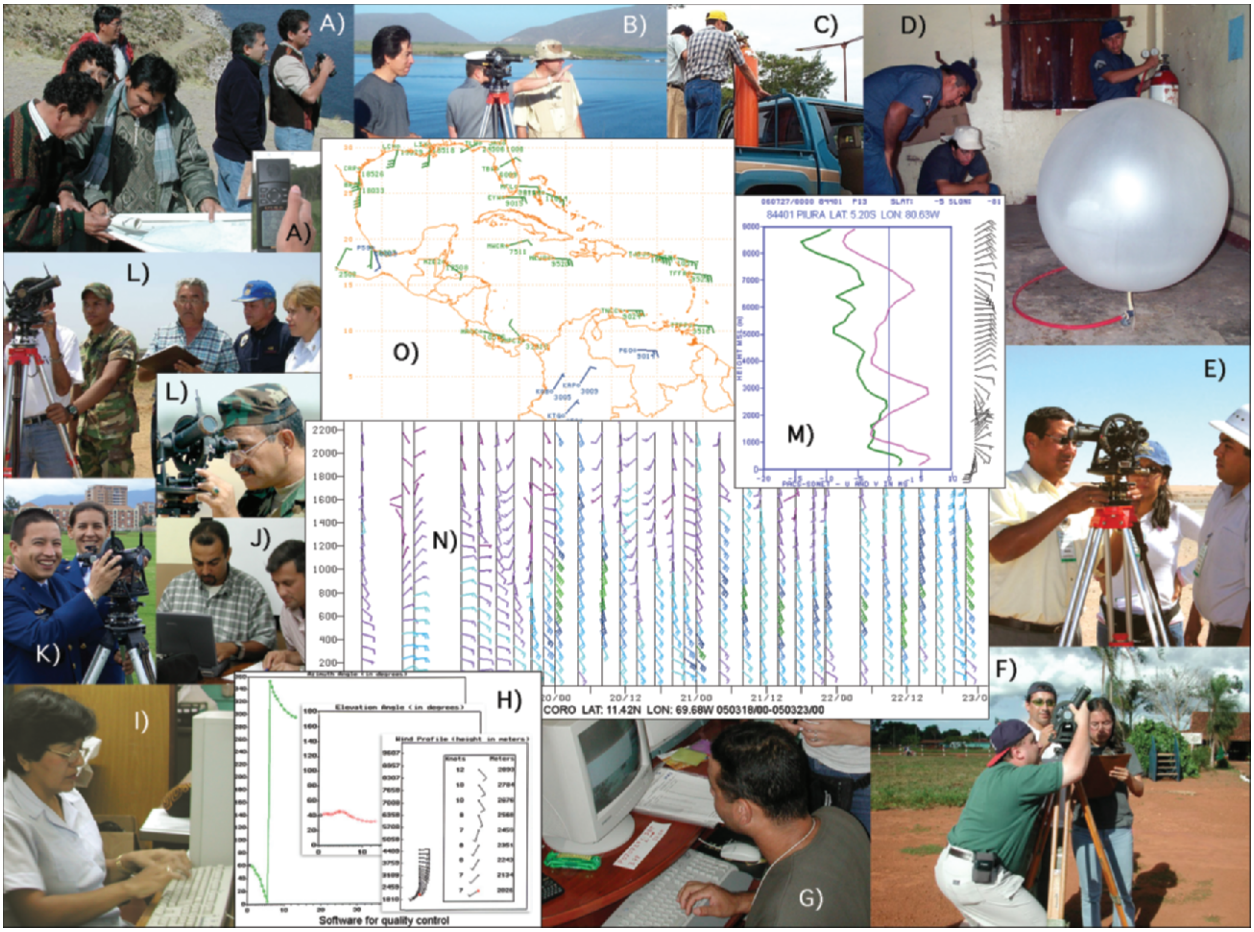

Fig. 4. Collage showing some of the PACS-SONET activities: (a) site selection for Lake Titicaca activity and a GPS, essential item for field work in map-poor regions; (b) setting up a site at Mexican Navy base at Topolobampo; (c) distributing gas via a 500-km pick-up ride in Paraguay; (d) inflating a balloon in Cd del Carmen, Mexico; (e) training observers near Arequipa, Peru; (f) SALLJEX training in San Ignacio, Bolivia; (g) processing raw pilot balloon data on computer; (h) examples of displays using the software to process the raw angle data; (i) data entry at operations center during a training course in Panama; (j) coursework in Panama; (k) training a new class of observers in Bogota, Colombia; (l) observers at San Fernando de Apure, Venezuela, during special experiment to describe diurnal cycle of low-level jet; (m) example of processed wind output; (n) 3-hourly time–height section of winds at Venezuelan site during special field campaign in 2005; (o) example of real-time map showing radiosonde (green) and pilot balloon (blue) data for Caribbean area in 2007.

Building on the unconventional lecture material, the students, working in groups, were tasked to design and justify their own meteorological service for a particular country, constrained by specific setup and annual operating budgets. This activity gave the students an understanding of the constraints involved in operating the PACS-SONET, and (it was hoped) an appreciation for the value of cost-effective observing systems.

Perhaps the most popular component of each course was a 3-day field program to expose the participants to designing and carrying out a meteorological field program to investigate a mesoscale circulation feature of regional interest. An additional objective was to ensure that each student understood the procedures involved in PACS-SONET, including the uncertainties involved in making and quality controlling the observations, and the potential value of the observations for low-cost meteorological research. In each experiment the students organized a pilot balloon observing network, made round-the-clock observations at the field sites, and analyzed, displayed, and synthesized the results. In Panama, the class operated four stations and an operations center, with the objective of describing 1) the sea–land breeze circulation and 2) the effect of high terrain in western Panama on the wind field. For the Bolivian course, a network of pilot balloon stations

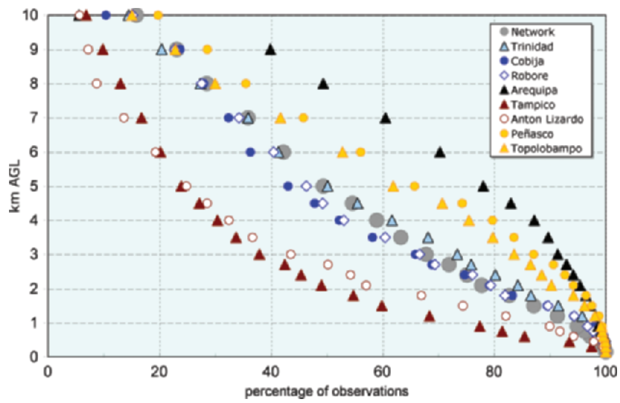

Fig. 5. Percentage of observations reaching any particular height, averaged over all PACS-SONET observations (gray dots) and for a selection of different PACS-SONET sites. See Fig. 2 for station locations.

made frequent observations around Lake Titicaca to describe the lake breezes circulation; convergence of the nocturnal land breezes over the lake appears to be responsible for the observed maximum in precipitation over the lake.

The essential goal of the educational program was to generate enough interest in the PACS-SONET observations to ensure that the data collection effort was sustained. It was thought that by establishing a network that could be maintained with minimal resources (compared with a radiosonde network) the network could be sustained by the countries of the region. Despite many positive comments on the value of the observations from individuals in the various countries, this enthusiasm at the forecaster level had limited impact on budgetary decisions at higher levels.

VALUE OF PACS-SONET OBSERVATIONS. The original and sustaining justification for the PACS-SONET was its potential value for supporting climate research activities. Some of the more unique aspects of the data collected to date are described below. More information on the project in general, together with the complete dataset, is available from the project's Web site (online at www.nssl.noaa.gov/projects/pacs).

Overall performance of the network. Approximately 50,000 pilot balloon observations were made as part of the PACS-SONET. The percentage of observations reaching any particular level can be seen from Fig. 5, from which it is apparent that 50% of the observations were tracked to 5 km AGL. Also plotted are values for selected stations to show the range of variability between sites. Of interest in this figure is the wide range in performance among the PACS-SONET stations. The two worst-performing stations of PACS-SONET (not a reflection of the observers but of the cloudiness!) were along the Gulf of Mexico, while much better statistics are shown from the two sites in northwestern Mexico. Also shown are statistics from three sites in the Bolivian lowlands, a relatively cloudy region. These show very similar profiles, indicating that the characteristics of

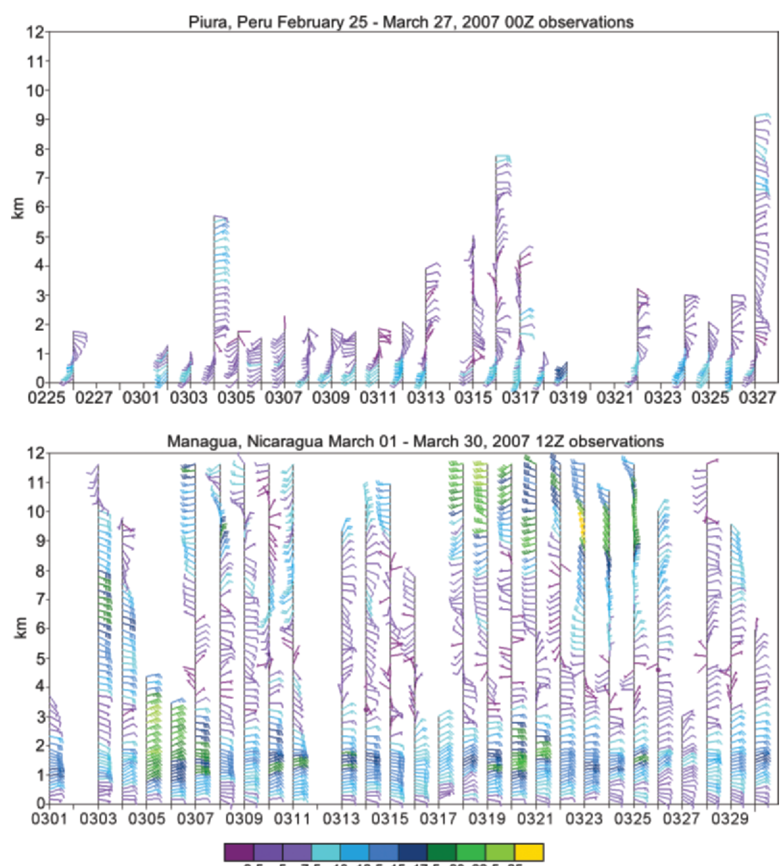

Fig. 6. Example of time–height sections of winds (plotting conventional) for two PACS-SONET sites during 30-day period, ~Mar 2007. One site is relatively cloudy (Piura, top) and the other relatively clear (Managua, bottom). Both plots use real-time data, but processed locally with special software to detect/correct obvious errors. Color bar: m s^{-1}. Vertical axis: km.

Table 2. Pilot balloon stations during the NAME and SALLJEX field programs and their main scientific objectives.

Station	Country	Institution	Latitude	Longitude	Elevation (m)	Period operating	Count of obs	Primary objective
NAME 2004								
Cataviña	Mexico	None	29.84°N	114.79°W	554	06/04–09/04	113	Estimation of eastern Pacific Ocean moisture fluxes
Hermosillo	Mexico	UEPCS	29.05°N	110.98°W	210	06/04–09/04	232	Estimation of eastern Pacific Ocean moisture fluxes
Empalme	Mexico	CNA	27.95°N	110.76°W	12	05/04–09/04	245	Estimation of eastern Pacific Ocean moisture fluxes
Tesopaco	Mexico	None	27.81°N	109.35°W	440	05/04–09/04	323	Diurnal circulation along slopes of Sierra Madre Occidental
Bahia Tortugas	Mexico	EPFBT	27.70°N	114.90°W	18	06/04–09/04	82	Estimation of eastern Pacific Ocean moisture fluxes
Santa Rosalia	Mexico	CBTIS	27.50°N	112.29°W	33	06/04–09/04	204	Estimation of eastern Pacific Ocean moisture fluxes
Cd Jimenez	Mexico	ITCDJ	27.13°N	104.86°W	1,380	06/04–09/04	171	Description of tropical wave variability over central Mexico
Huatabampo	Mexico	ITHUA	26.84°N	109.61°W	17	05/04–09/04	356	Estimation of eastern Pacific Ocean moisture fluxes
Choix	Mexico	EPUAS	26.72°N	108.31°W	250	06/04–09/04	185	Diurnal circulation along slopes of Sierra Madre Occidental
Loreto	Mexico	UABCS	26.10°N	111.33°W	7	06/04–09/04	149	Estimation of eastern Pacific Ocean moisture fluxes
Cd Lerdo	Mexico	ITSL	25.45°N	103.46°W	1,130	06/04–09/04	79	Description of tropical wave variability over central Mexico
Cd Constitucion	Mexico	CETIS	25.09°N	111.68°W	50	07/04–09/04	85	Estimation of eastern Pacific Ocean moisture fluxes
La Paz	Mexico	UABCS	24.15°N	110.24°W	15	06/04–09/04	121	Description of tropical wave variability
Durango	Mexico	ITD	24.00°N	104.60°W	1,885	07/04–09/04	152	Description of tropical wave variability over central Mexico
Matehuala	Mexico	CONALEP	23.65°N	100.82°W	1,544	06/04–09/04	144	Description of tropical wave variability over central Mexico
San Jose del Cabo	Mexico	ITESLC	23.06°N	109.62°W	95	07/04–09/04	83	Description of tropical wave variability and moisture fluxes
Maria Madre	Mexico	SMAM	21.76°N	106.54°W	2	07/04–08/04	75	Description of tropical wave variability and moisture fluxes
Lake Havasu City	USA	MCC	34.57°N	114.36°W	197	06/04–08/04	119	Describe quasi-permanent heat low variations over southwest United States
Gila Bend	USA	GBSD	32.96°N	112.70°W	262	08/04	17	Describe quasi-permanent heat low variations over southwest United States
Silver City	USA	WNMU	32.78°N	108.29°W	1,856	07/04–08/04	103	Describe quasi-permanent heat low variations over southwest United States
SALLJEX 2002–03								
Station	**Country**	**Institution**	**Latitude**	**Longitude**	**Elevation (m)**	**Period operating**	**Count of obs**	**Primary objective**
J.V. Gonzalez	Argentina	UBA	25.11°S	64.13°W	378	11/02–02/03	203	Describe variability of South American low-level jet
Pampa Guanacos	Argentina	UBA	26.23°S	61.84°W	168	11/02–02/03	295	Describe variability of South American low-level jet
Resistencia	Argentina	UBA	27.45°S	59.06°W	53	11/02–02/03	239	Describe variability of South American low-level jet
Santiago del Estero	Argentina	UBA	27.76°S	64.25°W	210	11/02–02/03	231	Describe variability of South American low-level jet
Tostado	Argentina	UBA	29.23°S	61.76°W	74	11/02–02/03	268	Describe variability of South American low-level jet
Chamical	Argentina	UBA	30.37°S	66.31°W	482	11/02–02/03	282	Describe Chaco heat low
Cordoba	Argentina	UBA	31.44°S	64.19°W	400	11/02–02/03	233	Describe variability of South American low-level jet
Parana	Argentina	UBA	31.83°S	60.52°W	111	11/02–02/03	293	Describe variability of South American low-level jet

Villamontes	Bolivia	AASANA	21.25°S	63.45°W	398	12/02–02/03	67	Describe Chaco heat low
Cruzeiro do Sul	Brazil	CPTEC	7.63°S	72.67°W	170	01/03–02/03	123	Describe variability of South American low-level jet
Rio Branco	Brazil	CPTEC	10.16°S	67.30°W	160	12/02–02/03	187	Describe variability of South American low-level jet
Vilhena	Brazil	CPTEC	12.74°S	60.15°W	600	01/03–02/03	232	Describe variability of South American low-level jet
Dourados	Brazil	CPTEC	22.23°S	54.82°W	454	01/03–02/03	104	Describe variability of South American low-level jet
Pucallpa	Peru	SENAMHI	8.42°S	74.60°W	149	12/02–02/03	177	Describe variability of South American low-level jet
Ica	Peru	SENAMHI	14.07°S	75.73°W	410	11/02–02/03	138	Describe circulation around altiplano
Puno	Peru	SENAMHI	15.86°S	70.00°W	3,812	11/02–02/03	117	Describe circulation over northern altiplano

Institution acronyms:

AASANA = Administration of Airports and Aerial Navigation Services
CBTIS = Industrial, Technological and Services Preparatory School
CETIS = Industrial, Technological and Services Education Center
CNA= National Water Commission
CONALEP = National Technical and Professional Education College
CPTEC = Center for Weather Forecasting and Climate Studies
UEPCS = State of Sonora Civil Protection
EPFM = Federal Elementary School of Bahia Tortugas
EPUAS = Preparatory School of the Autonomous University of Sinaloa
GBSD = Gila Bend School District
ITCDJ = Technological Institute of Ciudad Jimenez
ITD = Technological Institute of Durango
ITES = Higher Technological Institute of Los Cabos
ITHUA = Technological Institute of Huatabampo
ITSL = Higher Technological Institute of Lerdo
MCC = Mohave Community College
SENAMHI = National Meteorological and Hydrological Service
UABCS = Autonomous University of Baja California Sur
UBA = University of Buenos Aires
WNMU = Western New Mexico University

the cloudiness vary little across the region, at least in a manner that impacts pilot balloon observations.

Another perspective of the irregular nature of pilot balloon data can be graphically seen from time–height sections of the wind for a relatively cloud-free site and one that is quite cloudy (Fig. 6). This highlights one of the tenants of any pilot balloon network—a relatively large number of stations are needed to increase the odds of obtaining some high-altitude winds.

Mean field depiction. An example of the value of the PACS-SONET observations in defining the mean fields is shown in Fig. 7. Here the observations during one summer are shown from three sites in southeastern Mexico, where routine radiosonde observations are also available for comparison.

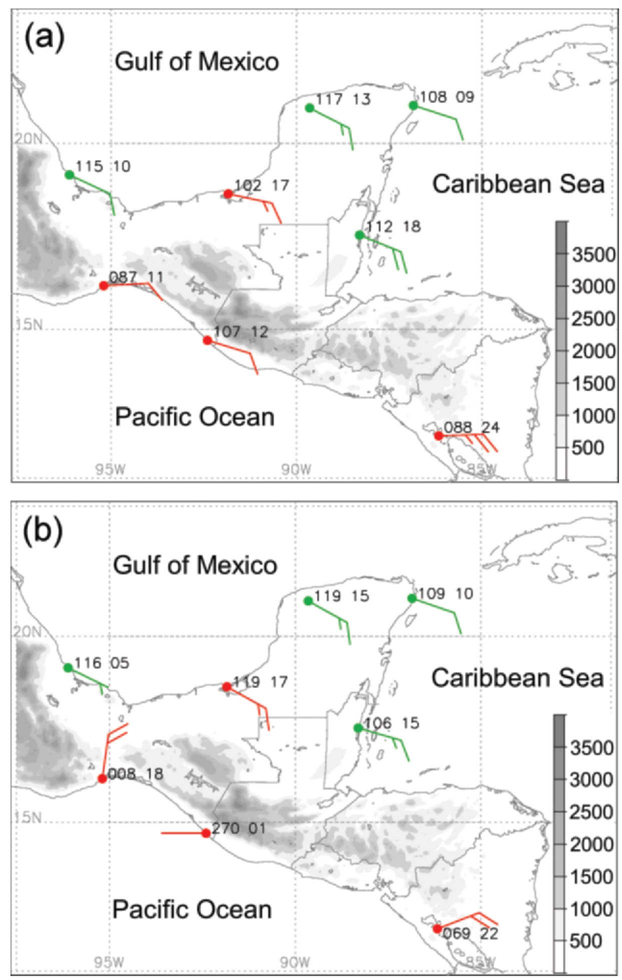

Fig. 7. Mean ~1200 UTC winds at (a) 3000 m and (b) 750 m above sea level, averaged over the period Jun–Aug 2000 around southeastern Mexico and northern Central America. Mean radiosonde-based winds are shown in green; PACS-SONET pilot balloon mean winds are in red. Numbers are direction in degrees and speed in knots (1 kt ~0.5 m s⁻¹). Shading is altitude in m.

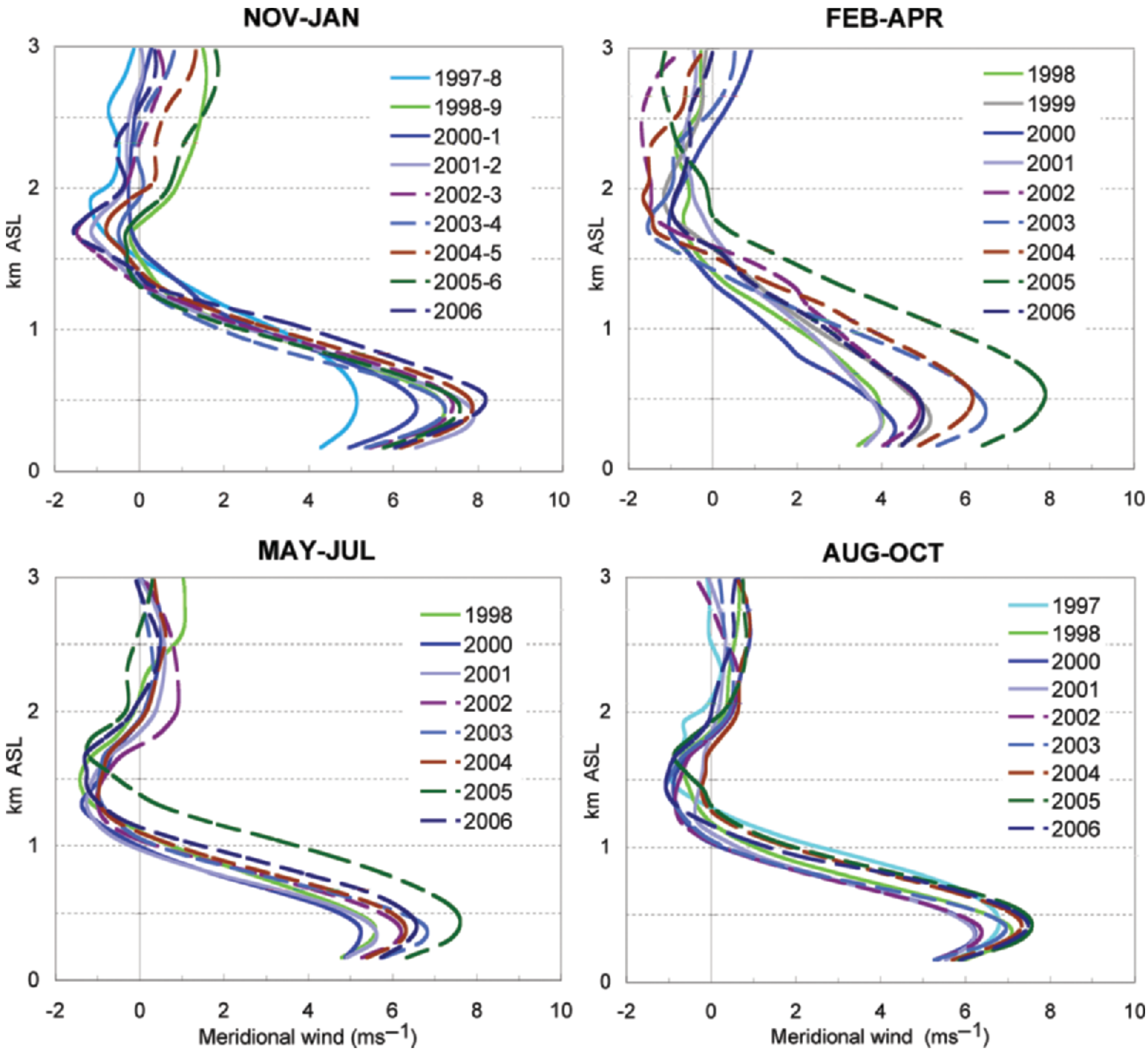

Fig. 8. Meridional wind profiles at Piura, Peru, averaged over 3-month intervals, for each of 8 yr of observations available for the site. Note the relatively large interannual variability during the warm season (Feb–Apr) and very small variability during the cool season (Aug–Oct).

The wind field at 3000 m above mean sea level (MSL) (~700 mb), which is above most terrain, is similar whether estimated separately from the pilot balloon or from the radiosonde observations. However, at 750 m MSL (~925 mb), the pilot balloon winds show features that are not evident in the radiosonde mean values, such as the northerly gap flow across the Isthmus of Tehuantepec and the weak westerly flow at Puerto Madero, in the lee of high mountains in extreme southeastern Mexico. Thus, PACS-SONET observations can help resolve the flow around regionally important topographic features.

Mean meridional wind near the equator. The station with the most complete record of observations (3,261 observations over almost 10 yr) among the PACS-SONET sites was that operated by the University of Piura, some 60 km inland on a relatively wide and flat coastal plain in northern Peru (~5.2°S). Frequent low clouds during the morning hours dictated afternoon observations at Piura, because these could be tracked higher. Figure 8 shows the mean meridional wind profiles for 3-month periods for each year from 1997 through 2006. The very small interannual variability stands out. Near the level of maximum winds (~400–500 m MSL) the variation is less than 2 m s^{-1} during the August–October period, and only slightly larger during May–July. The interannual variability is clearly larger during the warmest part of the year (February–April), and the difference between an El Niño year (1998) and a cool year (2005) is about 4 m s^{-1}. The fact that there is such small interannual variation of the

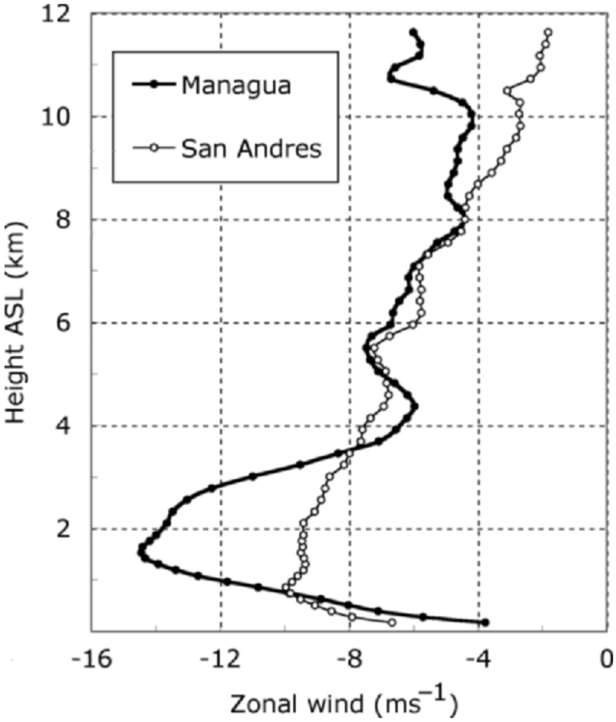

Fig. 9. Average Jul–Aug zonal wind profiles at Managua and San Andres Island, Colombia. Only observations made on the same day have been used to compute the means; 170 morning observations at the lowest level were common to both sites. Note the stronger winds at Managua, centered near 1600 m MSL, associated with gap flow across Central America. There is reasonable agreement from 5 to 8 km; above 8 km there are considerably fewer (less than 60) pilot balloon winds from Managua.

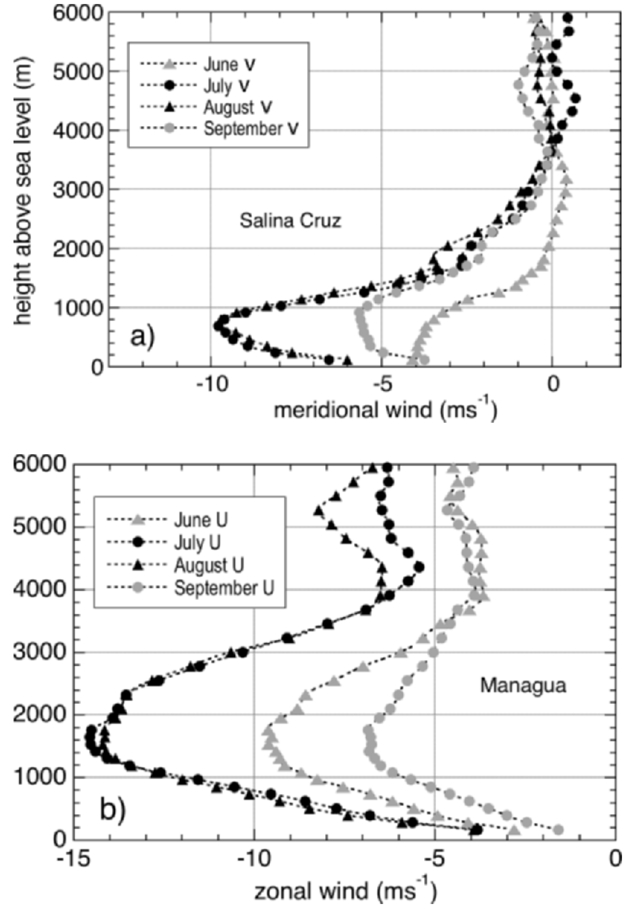

Fig. 10. Monthly mean cross-gap wind components at (a) Salina Cruz and (b) Managua. Note the extremely similar profiles during Jul and Aug at both sites. Both plots have the same horizontal and vertical scales; note the relatively shallow jet at Salina Cruz compared with Managua.

mean meridional circulation highlights the challenge to accurately measure such variability.

Gap flows across Central America. The pilot balloon site at Managua is situated in the widest low-altitude gap in the Central American cordillera. Observations here have shown the easterly trade wind flow to be considerably stronger in the 1–3 km MSL layer than that estimated from routine radiosonde observations at San Andres Island, less than 500 km to the east (Fig. 9). The relatively good agreement between the Managua and San Andres profiles at higher levels indicates that the difference in the wind profiles between the two sites is real and is associated with the channeling effect of topography.

The PACS-SONET stations at Managua and at Salina Cruz, the latter situated on the southern side of the Isthmus of Tehuantepec, both show strong gap flow, but at Salina Cruz it is primarily meridional, while at Managua it is zonal (Fig. 10). Both sites show the prominent strengthening of the gap wind flow during the months of July and August, associated with the Central American midsummer drought phenomenon that is most evident on the Pacific side of Central America (Magaña et al. 1999). A remarkable feature of the monthly mean wind profiles during July and August is that they are nearly identical within each gap, but the flow at Salina Cruz shows a peak at ~750 m, while at Managua the strongest winds are at ~1.5–2 km. Although the near-surface wind fields associated with these gap flows have recently been described from satellite scatterometer data (Romero-Centeno et al. 2007; Chelton et al. 2000) the PACS-SONET observations are unique in describing the detailed vertical structure of these flows.

Compositing studies using PACS-SONET data. PACS-SONET was originally established to help describe the relationship between variations in trade wind intensity and rainfall over Central America. By compositing winds from wet and dry days over the Pacific side of Central America during the wet season of 1997, it has been shown (Peña and Douglas 2002) that stronger and deeper cross-equatorial flow is associated with wet periods over Central America. Dry periods are likewise associated with stronger-than-normal trade wind flow across the region. Similar compositing procedures have recently been used to examine the heavy rainfall events over the coast of northern Peru and Ecuador during the 1998 El Niño event (Douglas et al. 2008).

FUTURE OF THE NETWORK. The annual budget of the PACS-SONET project was ~$300,000, approximately evenly split between observational expenses (some gas, all balloons, some observer stipends, travel, etc.), project staff and student support in Norman, Oklahoma, and NSSL indirect costs. Although this is a relatively small sum compared with many other field activities, it was well above the average annual cost of a PACS grant. We personally believe that the inability to transition the network from one supported entirely by research funds to one supported primarily by countries of the region was a key factor weighing against the continuance of the program.

The demise of PACS-SONET has implications for any long-term climate monitoring activity. If funded for research purposes, the research component of the program must be strong and argue effectively for continuation of the observations. The PACS-SONET activity primarily involved interaction with operational meteorological sectors—those institutions that we believed would have the capacity (personnel and budget) to carry out sustained observations. However, in Latin America most of these institutions have very limited research staff, and some have none at all. Thus, these institutions could not easily show the value of the observations through their own research.

PACS-SONET focused on countries where the meteorological sounding networks were poor or nonexistent, which was also where the meteorological research community was generally less developed. Predictably, this complicated developing strong two-way research collaborations, and without applied research showing the value of additional observations there was little motivation for the meteorological services to support such observations, however inexpensive they might be.

The current prospects for long-term sustainability of a research-oriented sounding network similar to the PACS-SONET are unclear. The meteorological theodolites and associated equipment remain deployed in their host countries, awaiting possible future use, and some meteorological services appear willing to support the activity. However, we believe that it is unrealistic to expect support from many national meteorological services as long as the value of meteorological soundings (either radiosonde or pilot balloon) for weather forecasting or climate monitoring cannot be clearly demonstrated to them in a quantitative manner. Central coordination and some external financial support is likely to be needed for any international network similar to PACS-SONET, and we believe that the United States will need to play a key role in such networks in the future.

ACKNOWLEDGMENTS. PACS-SONET funding was provided by the NOAA/Office of Oceanic and Atmospheric Research under NOAA-University of Oklahoma Cooperative Agreement #NA17RJ1227, U.S. Department of Commerce. The PACS program managers and other Office of Global Programs (now Climate Program Office) officials are thanked for supporting these activities. Malaquias Peña helped manage the network for the first several years, and Walter Fernandez at the University of Costa Rica was co-PI and helped arranged many of the Central American details during the first phase of the project. Joe Facundo at the U.S. National Weather Service arranged for the long-term loan of dozens of meteorological theodolites. The institutions mentioned in Table 1 are especially thanked for their very considerable efforts. Literally hundreds of individuals have helped throughout Latin America in implementing the network; even a long list would slight the many invariably left out. A more complete acknowledgment and list of country contacts can be found on the PACS-SONET homepage. Bob Maddox, former director of NSSL, supported the concept of inexpensive field programs, without which the early Mexican field programs, the predecessors of PACS-SONET, could not have been carried out.

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